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Processing and Ballistic Performance of Al_2O_3/TiB_2 Composites

by Gary A. Gilde and Jane W. Adams

ARL-TR-3658 September 2005

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5069

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REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED (From - To)**
September 2005	Final	October 2000–February 2003

4. TITLE AND SUBTITLE
Processing and Ballistic Performance of Al_2O_3/TiB_2 Composites

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Gary A. Gilde and Jane W. Adams

5d. PROJECT NUMBER
665857.031

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRD-ARL-WM-MD
Aberdeen Proving Ground, MD 21005-5069

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-3658

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Early research on Al_2O_3/TiB_2 composites focused on exploiting their potential as a low-cost armor ceramic. Limited ballistic data indicated that the microstructure had a dramatic effect on ballistic performance. In some cases, the penetration resistance of Al_2O_3/TiB_2 approached that of monolithic TiB_2 ceramics. However, challenges were encountered both in quantifying the microstructural details and fabricating the desired microstructure.
The large spread in depth of penetration results for these ceramics, coupled with an insufficient number of samples tested, led to some confusion in accessing the effect microstructure had on the ballistic performance. Our research focused on microstructure control during fabrication and a more thorough ballistic evaluation to correlate microstructure with penetration resistance. Composites were made from mixed Al_2O_3 and TiB_2 powders. The composites, prepared with dramatically different microstructures, had similar ballistic performance.
Results show that the penetration resistance of Al_2O_3/TiB_2 composites is not as good as a hot-pressed silicon carbide.

15. SUBJECT TERMS
ceramic composite, microstructure, armor

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Gary Gilde
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL	20	**19b. TELEPHONE NUMBER** (*Include area code*) 410-306-0923

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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1. Introduction

Composites of Al_2O_3/TiB_2 were produced by K .V. Logan at the Georgia Institute of Technology (*1*), and the University of Dayton Research Institute (UDRI) performed the initial depth-of-penetration (DOP) ballistic evaluations on them (*2*). Logan concluded that there could be a possible correlation between microstructure and ballistic performance. It was theorized that the composite structure that had TiB_2 distributed along the grain boundaries of the Al_2O_3, which formed a continuous distribution of TiB_2, exhibited better ballistic performance than when the TiB_2 was dispersed in the Al_2O_3 matrix. Those results led the U.S. Army to continue looking at the composite material and the role of microstructure. In some tests, the ballistic performance was greater than predicted from the rule of mixtures, as shown in figure 1, and was high enough to generate interest in these materials as potential armor ceramic (*3*). However, there was ambiguity as to whether the observed differences were due to random ballistic variation or to an actual difference in microstructure (*4*). The purpose of this work was to fabricate Al_2O_3/TiB_2 composites with two distinctly different microstructures, to correlate microstructural differences with ballistic performance, and to determine how well the composite material worked relative to other armor-grade ceramics.

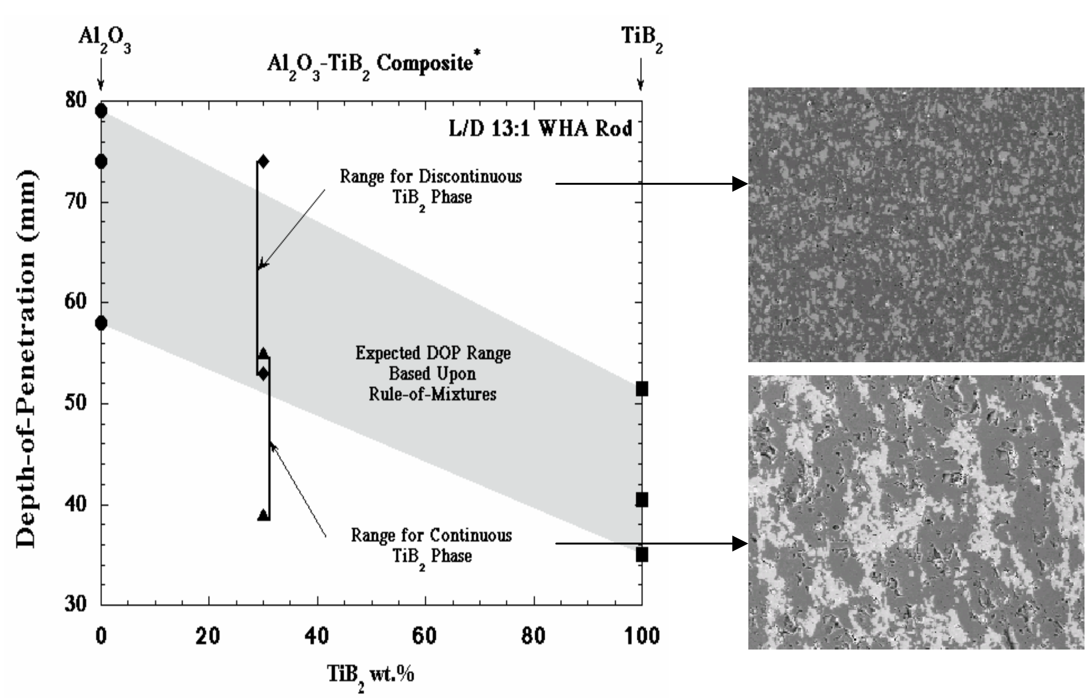


Figure 1. Early DOP ballistic test data for L/D = 13 rod at 1550 ms^{-1} against alumina titanium diboride ceramics.

2. Experimental

2.1 Processing

Al_2O_3/TiB_2 composites were fabricated with two different microstructures and then ballistically tested to determine the effect of the two different microstructures. The results from these ballistic tests were compared to earlier tests on similar materials made at the Georgia Tech Research Institute (GTRI). The materials from GTRI were the same thickness and tested under the same conditions by UDRI (*2*).

Two different powder-processing routes were used to produce composites with the same composition but very different microstructures. The composition was 77.4 without Al_2O_3[*] and 22.6 without TiB_2.[†] Traditional ball-milling was used to make a composite structure in which the TiB_2 was evenly dispersed within the Al_2O_3 matrix. This microstructure will be referred to as manually mixed (MM). The Al_2O_3 and TiB_2 powders were ball-milled in ethanol for 16 hr using alumina milling media in a polyethylene jar. The slurry was then dried and the powder sieved through a polyester USA Series 60 mesh sieve.

Electrostatic dispersion was used to make a composite structure in which the TiB_2 particles surrounded Al_2O_3 agglomerates. TiB_2 was added to the Al_2O_3 powder in a polyethylene jar and dry mixed for 30 min using a Turbula mixer.[‡] In electrostatic dispersion, the TiB_2 coats agglomerates of Al_2O_3 because of the positive charge (on TiB_2) and negative charge (on Al_2O_3) that build up on the particles during the dry mixing. The powder was then sieved through a USA Series 60 polyester mesh sieve. The composite microstructure that results, whereby the TiB_2 surrounded areas of AL_2O_3, was designated as electrostatically dispersed (ESD).

Powders from the two different mixing methods were then hot-pressed under the same conditions. The composites were hot-pressed in graphite dies in an argon atmosphere. The temperature was raised from 20 °C to 850 °C at 10 °C/min, and then from 850 C° to 1650 °C at 4 °C/min. The temperature was held at 1650 °C for 4 hr and then cooled down at 10 °C/min to 20 °C. A pressure of 35 MPa was applied to the powder compact at the beginning of the heating cycle and maintained through the final hold at 1650 °C, then released prior to cool down.

[*] A16SG, Alcoa, Pittsburgh, PA.

[†] Grade D, H. C. Starck, Newtown, MA.

[‡] Turbula Mixer, Glen Mills, Inc., Clifton, NJ.

2.2 Characterization

The elastic modulus was measured using the procedures described in ASTM C 1259 (*5*) and densities of the compacts were measured using the Archimedes water immersion technique. Samples were sectioned and polished for microstructural analysis. Microscopy was performed on a scanning electron microscope (SEM) using the backscatter mode.

DOP ballistic testing was conducted using a 65-g, L/D = 10 tungsten rods striking the sample at 1500 m/s. The rod was 7.8 mm in diameter, 78.7 mm long, and made from a tungsten heavy alloy (WHA) which was 93% W/ 4.9% Ni/ 2.1% Fe. The samples tested were 100 mm in diameter and 25 mm thick. These targets were mounted on rolled homogeneous armor (RHA) steel, semi-infinite witness blocks, with a thin layer of two-part epoxy. The target configuration is shown in figure 2. The velocity of the projectile and the pitch and yaw were determined using flash x-rays in all DOP tests. The maximum acceptable pitch-yaw angle was 1.5°.

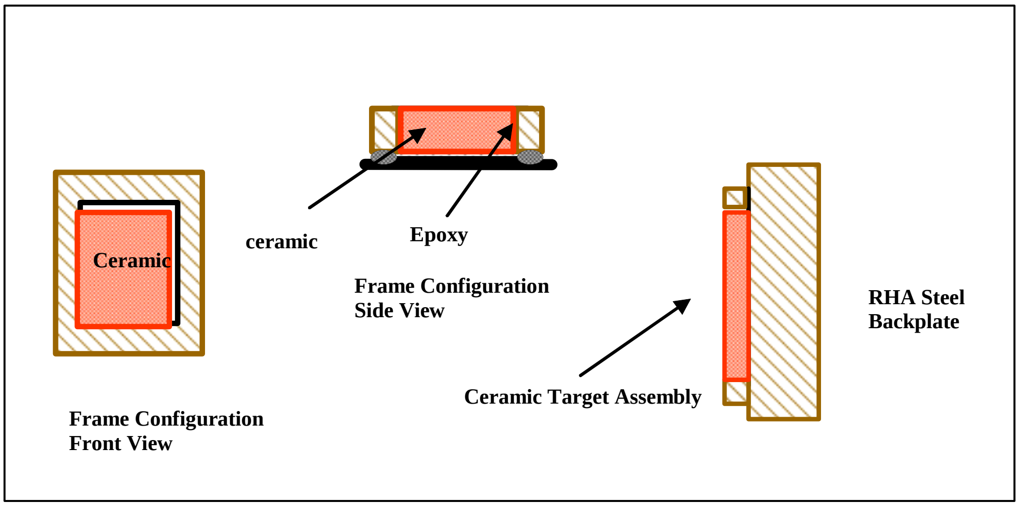


Figure 2. DOP test configuration.

From the DOP test data, mass efficiency, (e_m), space efficiency (e_s), and quality factor (q^2) can be defined by the following equations (*6*):

$$e_s = \frac{P_{WITN} - P_R}{T_{CER}} \quad , \tag{1}$$

$$e_m = \frac{(P_{WITN} - P_R) \times \rho_{WITN}}{T_{CER} \times \rho_{CER}} = e_s \times \frac{\rho_{WITN}}{\rho_{CER}} \quad , \tag{2}$$

and

$$q^2 = e_m \times e_s \quad , \tag{3}$$

where P_{WITN} is the DOP of the projectile into the semi-infinite witness plate without the ceramic facing; P_R is the penetration of the projectile into the semi-infinite witness plate with the ceramic mounted to the front face; T_{CER} is the thickness of the ceramic applied to the face of the witness plate; and ρ refers to the density of the respective materials. It can be seen that e_m and e_s are dimensionless factors that compare the ballistic performance to RHA steel. The e_m and e_s of the reference witness plate are 1; thus, a higher number denotes better ballistic performance as compared to the reference backing material. Because both the weight of the armor and the space it takes up are critical factors in designing armors, the armor quality factor, q^2, is important to armor designers because it relates both the mass and space efficiencies.

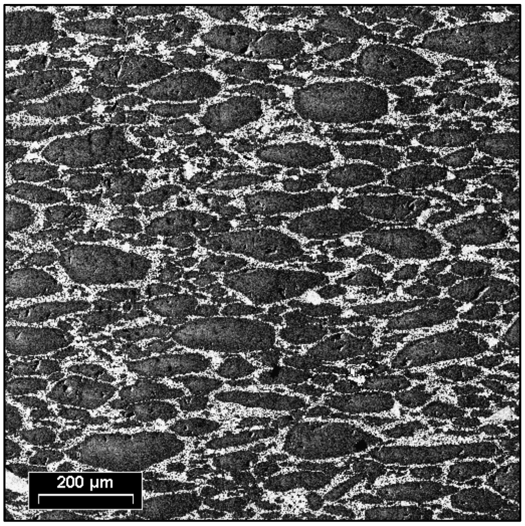
Pieces of the ceramic were recovered after the ballistic test. The pieces were sectioned, mounted, and polished. Microstructural characterization was performed using an SEM in the backscatter mode.

3. Results and Discussion

This study used the same Al_2O_3/TiB_2 composition to produce two different microstructures and to investigate the effect of microstructure on the ballistic performance. Results show that the only significant difference in the two composites is the microstructure. The density and the elastic modulus of the different composites were measured. The density of the microstructures were equivalent: both the MM composites and the ESD composites had a density of 4.0 g/cm^3. The theoretical density for the composite, as determined by the rule of mixtures, was 4.1 g/cm^3. In addition to having a similar density, the elastic moduli were similar.

Figure 3 shows that the microstructure for the ESD composite is very different from the MM composite. In the MM composite, the TiB_2 is dispersed uniformly within the Al_2O_3 matrix. In the case of the ESD composite, the TiB_2 surrounds large agglomerates of Al_2O_3, forming a continuous TiB_2 phase around islands of Al_2O_3. This structure is developed in the electrostatic dispersion due to the static electricity that builds up on the particles during the dry Turbula mixing; charge differences fix the TiB_2 to the Al_2O_3 agglomerates. When this powder is hot-pressed, the TiB_2 coating on the Al_2O_3 agglomerates is maintained.

Ballistic properties of Al_2O_3/TiB_2 composites impacted with the L/D = 10 tungsten alloy rod at 1500 m/s are presented in figure 4. It can be seen that there is no significant difference in the ballistic performance of the two composites. The average penetration for the MM composite is 32 mm with a standard deviation of 8 mm vs. 34 mm with a standard deviation of 4 mm for the ESD composite. The spread in the data is the same for the hot-pressed silicon carbide tested, which had an average penetration of 29 mm and a standard deviation of 8. This hot-pressed silicon carbide is a mature, commercially available, armor ceramic. This variation is typical of ceramic materials tested in a DOP test.



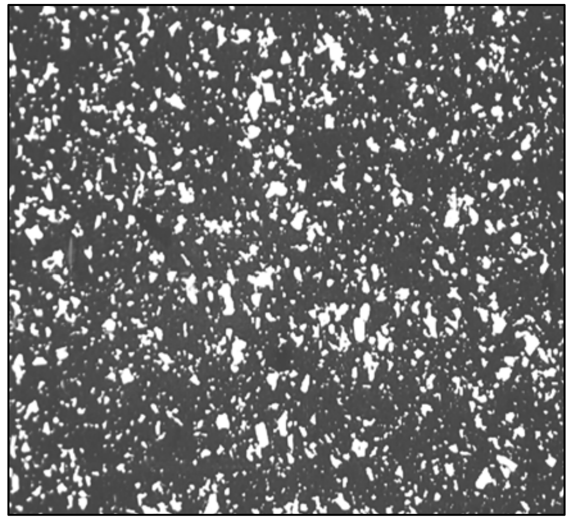


Figure 3. Microstructure of ESD composite on left and MM composite on right.

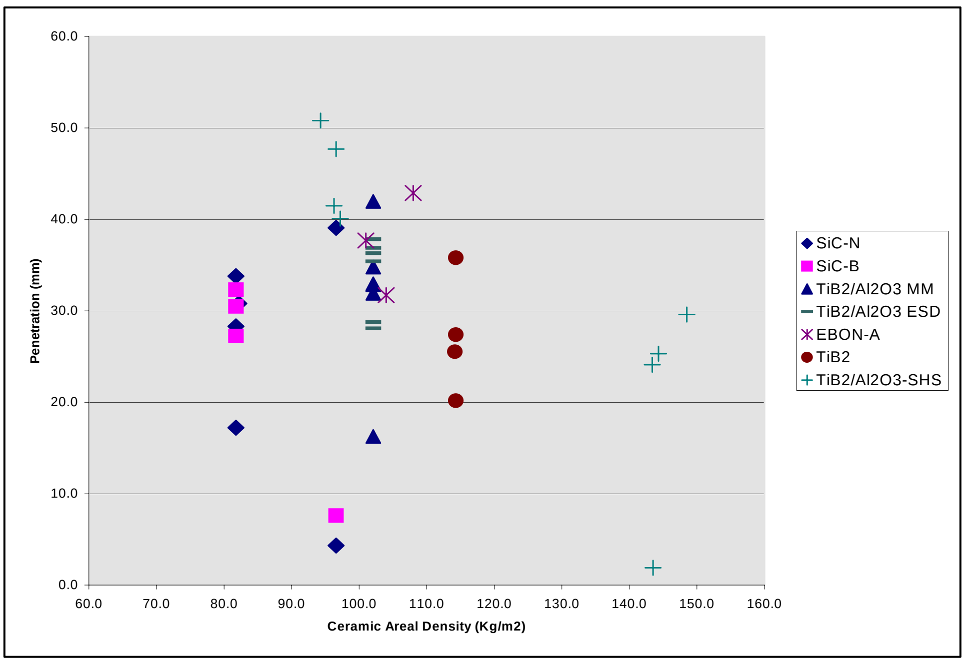


Figure 4. Summary of DOP experiments as described in experimental procedure: penetration into RHA backing vs. ceramic areal density against the L/D = 10 rod at 1500 ms^{-1} (*4*).

Palicka and Rubin reported the average DOP of hot-pressed Al_2O_3 as 37.4 mm for an areal density around 108 kg/m^2 tested under similar conditions (*7*). The average DOP of a hot-pressed Al_2O_3 is greater as compared to the average DOP for Al_2O_3/TiB_2, however, all alumina DOP results fall within the range of DOP results for the composites. It is not certain that the addition of TiB_2 increases the ballistic performance, although it appears likely that it has some positive effect. The large spread in DOP data for ceramics makes it difficult to draw conclusions based on a small number of tests; comparisons based on a couple of ballistic tests are very suspect. Unfortunately, due to the costs and complexity of the ballistic testing, this is often done.

Determining the effect of the TiB_2 on the Al_2O_3 matrix was outside the scope of this investigation.

In this study there was no significant difference in ballistic performance of the composites tested despite very different microstructures that were produced. When these results are compared to the earlier testing conducted by UDRI on materials furnished by GTRI, the results are similar (*2*). Those tests were done on tiles of the same thickness using the same 65-g WHA test rod striking the target at 1500 m/s. The target configurations were similar; thus, a direct comparison of the ballistic results is possible. The composites furnished by GTRI were made using a composite powder formed using a self-propagating high-temperature synthesis (SHS) reaction (*1*). The average e_m for the SHS Al_2O_3/TiB_2 composites tested by UDRI was 3.0 and the highest e_m was 4.1. Logan (*1*) concluded that the microstructure of the tile that gave the e_m of 4.1 was different from the others tested because it had a greater amount of TiB_2 surrounding the Al_2O_3. She postulated that the superior ballistic performance was due to the greater amount of TiB_2 distributed around the Al_2O_3. The average e_m of the Al_2O_3/TiB_2 composites tested in the current study was 3.0 and the highest e_m was 4.3. However, the e_m of 4.3 was given by a composite where the TiB_2 is dispersed in the Al_2O_3. As can be seen in figure 5, the microstructure of the composite formed using the SHS-derived powder is different from the two microstructures tested in our study. The premise that the difference in ballistic performance is due to the difference in microstructure has not been supported by this study. In fact, the observed difference falls within the expected spread of DOP results for ceramics.

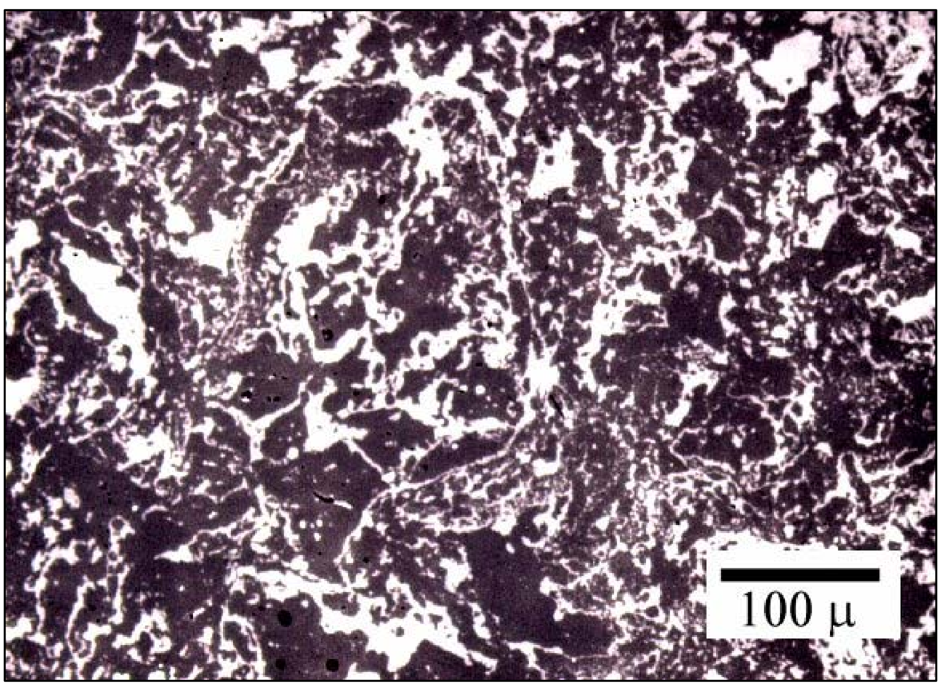


Figure 5. Microstructure of Al_2O_3/TiB_2 composite made from SHS-derived powder.

In previous work performed in our laboratory, composites prepared by GTRI were tested using a larger WHA L/D = 13 projectile that is 30% longer and twice the mass of the L/D = 10 projectile. The ceramic targets were 40 mm thick vs. 25 mm used in this study. The results are shown in figure 1. Composite targets were made using both mixed Al_2O_3/TiB_2 powders and composite powders formed via an SHS reaction. The best e_m obtained with the larger projectile, $e_m = 4.4$, is very close to the best e_m (4.3) in the current study, despite the differences in the testing. The average e_m in that study was 3.3, compared to an average e_m of 3.0 in this study. Although it is not possible to make direct comparisons when there are differences in the projectile and target thickness, in this case it is safe to conclude that the differences observed in the ballistic performance were due to the usual random variation in ceramic DOP results and not due to differences in microstructure. In this study, our highest e_m was given by the microstucture that had TiB2 dispersed within the Al_2O_3 (MM) as opposed to the previous study where the best e_m was given by the composites made with mixed Al_2O_3/TiB_2 powders where the TiB_2 was surrounding the Al_2O_3. This indicates that the observed differences in ballistic performance are due to the inherent variability in ceramic DOP tests. Because of the large spread in the DOP results for ceramics, extreme care must be taken when analyzing the data, and the sample size must be large enough to get a good indication of the standard deviation.

When the ballistic performance of the Al_2O_3/TiB_2 composite is compared to a hot-pressed silicon carbide, the silicon carbide is clearly superior. From figure 4 it can be determined that silicon carbide has an average e_m of 4.5, e_s of 1.8, and a q^2 of 8.3, while the Al_2O_3/TiB_2 composite has an average e_m of 3.0, e_s of 1.5, and a q^2 of 4.6.

Although none of the Al_2O_3/TiB_2 composites microstructures tested in this study had an effect on the ballistic performance, more work is needed to understand the effect of microstructure on ballistic performance. It would be a mistake to conclude that because the different microstructures tested in this study had no effect, microstructure will not have an effect on ballistic performance.

4. Summary

Our investigation to assess the effect of microstructure on Al_2O_3/TiB_2 composite ballistic performance demonstrated that distinctive microstructures could be developed and controlled by a variety of processing methods. A systematic ballistic evaluation was completed using 65-g L/D = 10 projectiles at a velocity of 1500 m/s. None of the microstructures tested had an effect on the ballistic properties of the composites. The process of mixing dry powders to electrostatically disperse the TiB_2 around the Al_2O_3 grains resulted in composite structures that were as effective as those that had the TiB_2 dispersed in the Al_2O_3, and both proved similar to composites made for powders derived for SHS reactions. The addition of TiB_2 to the Al_2O_3 matrix had no deleterious effect on the ballistic performance and may have enhanced the ballistic

performance of the Al_2O_3 matrix. Al_2O_3/TiB_2 composites do not result in $e_{m,}$ e_s, and q^2 values as high as a state-of-the-art hot-pressed silicon carbide and it may be concluded that Al_2O_3/TiB_2 composite structures will not be as effective as hot-pressed silicon carbide as an armor ceramic.

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